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*Tips, tricks, and techniques from the analog signal-path experts*

No. 108

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## Low-Voltage Current Loop Transmitter

— By Walt Bacharowski, Applications Manager

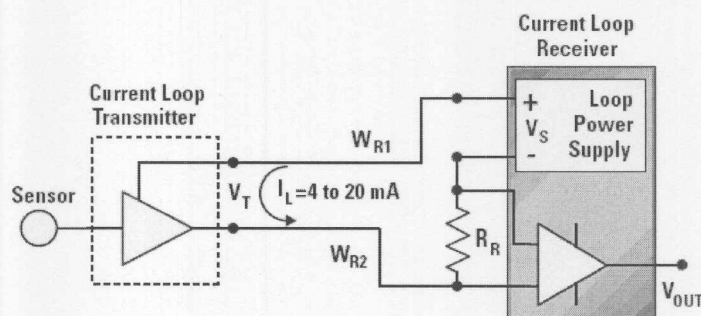


Figure 1. Current Loop Components and Connection

The 4 to 20 mA current loop, which is used extensively in industrial and process control systems, creates challenges for maximizing the operating loop length. In some cases, a very long loop is required and the combination of limited loop-power supply voltage and excessive loop wire resistance prevents its use. This article discusses the use of low-voltage amplifiers to minimize the transmitter's operating voltage requirements, which will maximize the operating loop length.

Typically, the current loop is powered from the receiver side while the transmitter controls the current flowing in the loop to indicate the value of the physical parameter being measured by the sensor. *Figure 1* shows the basic components and connection of a current loop.

The maximum distance between the transmitter and receiver is dependent on the power supply voltage ( $V_S$ ), and the sum of the loop drops, which are the minimum transmitter voltage ( $V_T$ ), the voltage drops across the wire resistance ( $W_{R1}$  and  $W_{R2}$ ), and receiver resistor ( $R_R$ ). In equation form:

$$\text{EQ1} \quad V_S = V_{WR1} + V_T + V_{WR2} + V_{RR}$$

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## Low-Voltage Current Loop Transmitter

Substituting the loop current and loop resistances into EQ1:

$$\text{EQ2} \quad V_S = I_L W R_1 + V_T + I_L W R_2 + I_L R_R$$

Given the wire's resistance in X Ohms per foot, the maximum loop current of 20 mA, the value of  $R_R$  equal to  $10\Omega$ , and the equal lengths of wire, EQ2 can be rearranged to calculate the maximum loop distance in terms the loop parameters:

$$\text{EQ3} \quad ft = \frac{V_S - V_T - 0.2}{0.04 (X \Omega/ft)}$$

EQ3 illustrates three ways to increase the maximum loop length: (1) increase the loop power supply voltage, (2) increase the wire gage, which will reduce the wire's ohms per foot, or (3) reduce the minimum voltage required for the current loop transmitter operation, which is the focus of the following section.

The use of low voltage amplifiers, such as the LMV951, and low drop out voltage regulators, such as the LP2951, can reduce the minimum voltage required for the current loop transmitter. Figure 2 shows the schematic of a loop-powered 4 to 20 mA transmitter, which will function with a minimum of 1.9V, and a 4 to 20 mA receiver.

In this example, a temperature sensor, such as the LM94022, provides a signal for the transmitter.

The components A1, Q1, and R1 through R5 form a voltage-to-current converter. The noninverting input of A1, pin 3, is the summing node for three signals, the loop current, offset current, and sensor signal voltage. The resistor R2 is the current shunt that measures the current flowing in the loop and is fed back through R3. The total loop current is the sum of the currents flowing in resistor R2 and R3,  $I_L = I_{R2} + I_{R3}$ . The amplifier, A1, forces the voltages at its inputs, pins 3 and 4, to be equal by forcing more or less current through R2. The result is that R2 and R3 have the same voltage across them. The ratio of the currents in R2 and R3 is the inverse of the resistor ratio:

$$\text{EQ4} \quad \left( \frac{I_{R2}}{I_{R3}} = \frac{R_3}{R_2} \right)$$

This highlights that the current in R3 is also part of the voltage-to-current conversion and is not an error current. An error source that will affect the loop current is the offset voltage of amplifier A1, which will add an error current to the loop current. At the minimum loop current of 4 mA, the voltage  $V_2$  is very close to 0.040V.

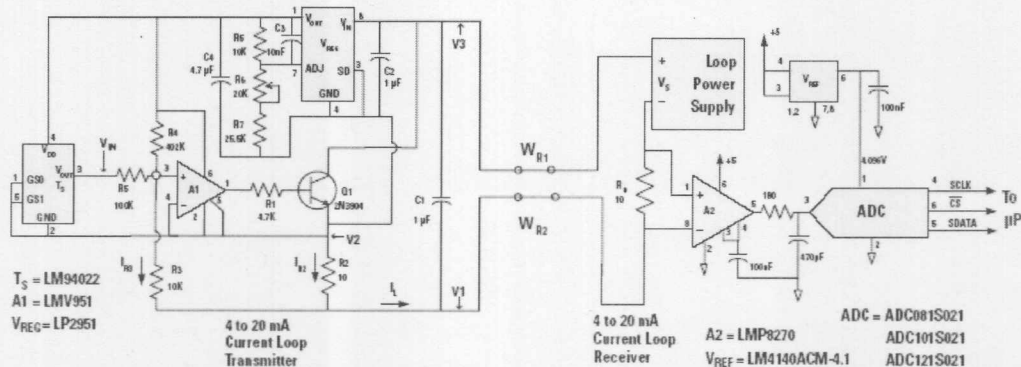


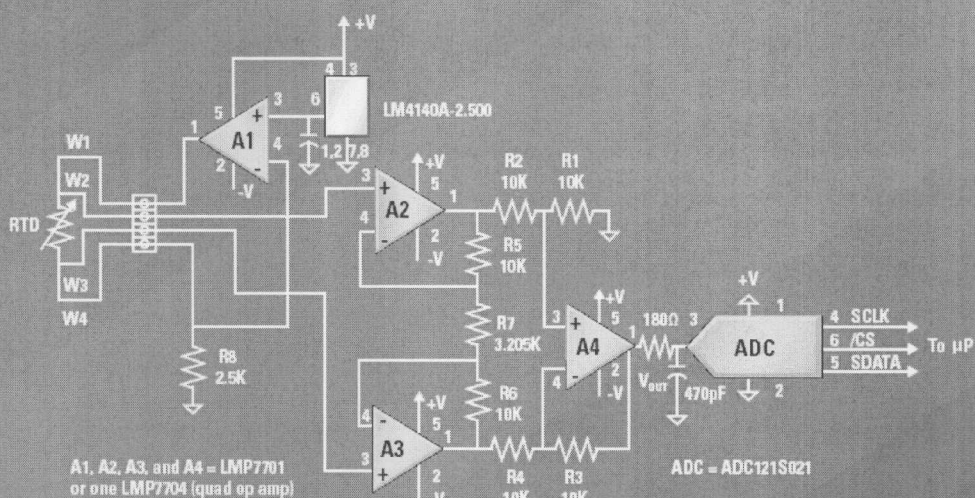
Figure 2. Loop-Powered Transmitter Schematic

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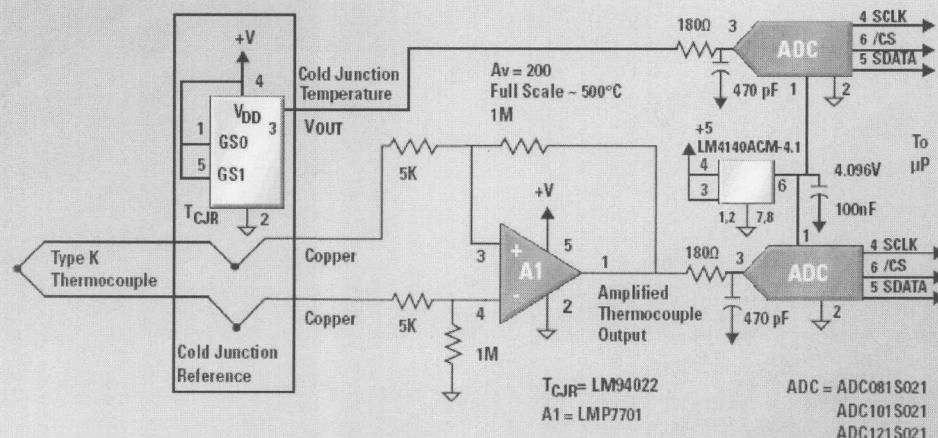
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## Solutions for Factory Automation

### Resistance Temperature Detector Application



### Thermocouple Temperature Detector Application



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## Precision Op Amps

Product ID	Max VOS Room Temp (µV)	TCV <sub>OS</sub> (µV/°C)	Specified Supply Voltage Range (V)	PSRR (dB)	CMRR (dB)	Gain (dB)	GBWP (MHz)	Voltage Noise (nV/√Hz)	I <sub>BIAS</sub> Room Temp (pA)
LMP2011/12/14	25	0.015	2.7 to 5.25	120	130	130	3	35	-3
LMP7701/02/04	200	1	2.7 to 12	100	130	130	2.5	9	0.2
LMP7711/12	150	-1	1.8 to 5.5	100	100	110	17	5.8	0.1
LMP7715/16	150	-1	1.8 to 5.5	100	100	110	17	5.8	0.1

## Precision Current Sense Amps

Product ID	Input Voltage Range	TCV <sub>OS</sub> (µV/°C)	Fixed Gain (V/V)	Supply Voltage (V)	CMRR (dB)	Packaging
LMP8275	-2 to 16	30	20	4.75 to 5.5	80	SOIC-8
LMP8276	-2 to 16	30	20	4.75 to 5.5	80	SOIC-8
LMP8277	-2 to 16	30	14	4.75 to 5.5	80	SOIC-8

## Low-Voltage Op Amps

Product ID	Typ I <sub>s</sub> / Channel (µA)	Total Specified Supply Range (V)	Max V <sub>OS</sub> (mV)	Max I <sub>BIAS</sub> Over Temperature	Typ CMVR (V)	GBW (MHz)	Packaging
LMV651	110	2.7 to 5.5	1	80 nA (typ)	0 to 4.0	12	SC70-5, TSSOP-14
LMV791	1150/0.14	1.8 to 5.5	1.35	100 pA	-0.3 to 4.0	17	TSOT23-6, MSOP-10
LMV796	1150	1.8 to 5.5	1.35	100 pA	-0.3 to 4.0	17	SOT23-5, MSOP-8
LMV716	1600	2.7 to 5.0	5	130 pA	-0.3 to 2.2	5	MSOP-8
LPV531	425	2.7 to 5.5	4.5	10 pA	-0.3 to 3.8	4.6	TSOT23-6

## ADCs for Single-Channel Applications

Product ID	Res	# of Inputs	Pin/Function Compatible	Throughput Rate (kSPS)	Input Type	Max Power 5V/3V (mW)	Supply (V)	Max INL (LSB)	Min SINAD (dB)	Packaging
ADC121S101	12	1	↑	500 to 1000	Single ended	16/4.5	2.7 to 5.25	±1.1	70	SOT23-6, LLP-6
ADC121S051	12	1		200 to 500	Single ended	15.8/4.7	2.7 to 5.25	±1.0	70.3	SOT23-6, LLP-6
ADC121S021	12	1		50 to 200	Single ended	14.7/4.3	2.7 to 5.25	±1.0	70	SOT23-6, LLP-6
ADC101S101	10	1		500 to 1000	Single ended	16/4.5	2.7 to 5.25	±0.7	61	SOT23-6
ADC101S051	10	1		200 to 500	Single ended	13.7/4.3	2.7 to 5.25	±0.7	60.8	SOT23-6
ADC101S021	10	1		50 to 200	Single ended	12.6/4	2.7 to 5.25	±0.6	60.7	SOT23-6
ADC081S101	8	1		500 to 1000	Single ended	16/4.5	2.7 to 5.25	±0.3	49	SOT23-6
ADC081S051	8	1		200 to 500	Single ended	12.6/3.6	2.7 to 5.25	±0.3	49	SOT23-6
ADC081S021	8	1	↑	50 to 200	Single ended	11.6/3.24	2.7 to 5.25	±0.3	49	SOT23-6
ADC121S625*	12	1		50 to 200	Differential	2.8	4.5 to 5.5	±1.0	68.5	MSOP-8
ADC121S705*	12	1		500 to 1000	Differential	16.5	4.5 to 5.5	±.95	69.5	MSOP-8

\*Differential input, 200 to 500 kSPS throughput rate forthcoming

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## Low-Voltage Current Loop Transmitter

An offset voltage of 1 mV in A1 will cause an error of about 2.5% in  $I_{R3}$ :

$$\text{EQ5} \quad \frac{0.001V}{0.040V} \times 100 = 2.5\%$$

Because the ratio of  $I_{R2}$  to  $I_{R3}$  is 1000 to 1, an error of 2.5% in  $I_{R3}$  results in a 0.0025% error in the loop current.

The voltage supply requirements for the components in transmitter must be evaluated in order to determine the minimum operating voltage required by the transmitter. For this example, a full-scale sensor input signal of 1.6V is used and results in a 10 mA per volt scale factor:

$$\text{EQ6} \quad \frac{I_{L\text{MAX}} - I_{L\text{MIN}}}{V_{IN\text{MAX}} - V_{IN\text{MIN}}} = \frac{20\text{ mA} - 4\text{ mA}}{1.6V - 0V} = \frac{16\text{ mA}}{1.6V} = 10\text{ mA/V}$$

The minimum voltage required for the transmitter ( $V3 - V1$ ) is the highest voltage requirement of the two paths from  $V3$  to  $V1$ . Path one is from  $V3$  to  $Q1$  and  $R2$  to  $V1$ . At the maximum loop current of 20 mA, the voltage drop across  $R2$  is 0.2V ( $V2$ ) and a collector emitter voltage of about 0.5V to stay out of saturation is a total of 0.7V. The second path is  $V2$  plus the output voltage of the voltage regulator and its dropout voltage. The full-scale sensor input signal of 1.6V requires about a 1.65V output from the regulator and the dropout voltage of the voltage regulator is less than 50 mV. The path has a minimum voltage requirement of 1.9V ( $0.2 + 1.65 + 0.05$ ). Note that the minimum operating voltage of the LMV951 is 0.9V so the minimum transmitter voltage could be reduced to about 1.3V by increasing the scale factor to 18 mA per volt. This is supported by the voltage regulator,  $V_R$ , which can be adjusted down to 1.25V, and with a dropout voltage of 50 mV, the loop transmitter can work down to 1.3V. The current loop transmitter functions by summing three signals: the loop current ( $R3$ ), the offset current ( $R4$ ), and the sensor ( $R5$ ).

The loop current generates a voltage drop across resistor  $R2$  such that  $V1$  is negative with respect to  $V2$  and then fed back through  $R3$ .

$$\text{EQ7} \quad V1 = V2 - R2(I_L)$$

The 4 to 20 mA current loop uses the offset current level of 4 mA to represent zero signal input. This is used as an open loop fault condition since zero current is a broken wire, transmitter failure, or another fault. The resistor  $R4$  is connected to the output of the adjustable low drop-out voltage regulator to create the 4 mA offset current. Resistor  $R4$ , at 402 k $\Omega$ , sets approximately a 4 mA offset current when the output of the voltage regulator is 1.65V. The variable resistor  $R6$  is used to set the loop current to 4 mA when the input signal is at zero volts. This adjustment compensates for error in the voltage regulator's output and resistor tolerance in  $R4$ ,  $R5$ , and  $R7$ . The offset can be calibrated to 4 mA by measuring the voltage across  $R_R$  and adjusting  $R6$  until the voltage across  $R_R$  is equal to 0.04V. The value of resistor  $R4$  can be calculated for other supply voltages by equating the voltages at the amplifier's input pins and rearranging to solve for  $R4$ :

$$\text{EQ8} \quad R4 = \frac{R3 \times V_{OUT}}{R2 \times I_{R2}} - R3$$

The resistor  $R5$  is used to scale the signal input voltage to the 16 mA span of the loop current, and in this example, it is assumed the input signal span is 1.6V. The equation for calculating  $R5$  can be developed by equating the voltages at the amplifier's input pins and rearranging to solve for  $R5$ .  $V_{IN}$  is the maximum signal input, 1.6V for this example, and  $I_{R2}$  is the change in output current, 16mA:

$$\text{EQ9} \quad R5 = \frac{R3 \times V_{IN}}{R2 \times I_{R2}}$$

This equation also indicates that changing the value of  $R5$  can change the full-scale input voltage. A low resistance variable resistor could be used in

series with R5 to add a full-scale calibration as shown in the following schematic (Figure 3).

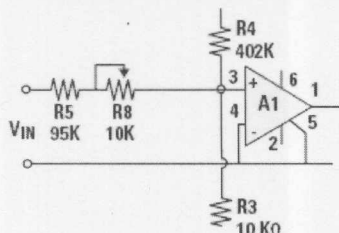


Figure 3. Input Calibration

In this example, a silicon temperature sensor is used as a signal source. The LM94022 is a low voltage, programmable gain temperature sensor that can be used to measure temperature from  $-50^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ . The schematic in Figure 2 shows the LM94022's gain select pins connected to ground, or the lowest gain. With this gain, the sensor's output ranges from 1.299V for a temperature of  $-50^{\circ}\text{C}$  to 0.183V for a temperature of  $150^{\circ}\text{C}$ .

As shown in Figure 1, the current loop transmitter accounts for only part of the voltage drop in the loop. The current loop receiver frequently uses a resistor,  $R_R$  in Figure 1, to generate a voltage drop that is used to measure the loop current. The measurement of the voltage across  $R_R$  can present some problems such as high common mode voltages, due to the loop power supply, as well as induced voltages from the environment. To overcome these measurement problems a differential amplifier, such as the LMP8270, can be used. The LMP8270 is a high common mode voltage differential amplifier with a fixed gain of 20. The gain of 20 also reduces the resistance of  $R_R$ , which reduces the loop voltage drop.

Referring to Figure 2, the voltage across resistor  $R_R$  is recovered from whatever common mode voltage exists on the current loop, up to 28V, and is amplified and drives the input to an Analog-to-Digital Converter (ADC). Internal to the LMP8270 is a differential amplifier with a gain of 10 followed by an amplifier with a gain of two. The internal connection between the two amplifiers is

brought out to pins 3 and 4. Also internal to the LMP8270 is a  $100\text{ k}\Omega$  resistor in series with the output of the first amplifier. A low pass filter is easily implemented by connecting a capacitor from pins 3 and 4 to ground.

Figure 2 shows a 4.096V reference being used by the ADC, representing the full-scale input. The differential input voltage to the LMP8270 for a 4.096V output is  $4.096/20 = 0.2048\text{V}$ . The value of  $R_R$  for a voltage drop of 0.2048V at a current of 20 mA is  $0.2048/20 = 10.24\Omega$ . A  $10\Omega$  resistor is used because it is a standard precision value. The result is an output voltage from A2 of 0.8V to 4.0V for a loop current of 4 mA to 20 mA.

The current loop transmitter was calibrated using the end points, 0V and 1.6V, as the input voltages while measuring the voltage across the  $R_R$  resistor. With 0.0V applied to the input the resistor  $R_6$  is adjusted until 40 mV is across  $R_R$ . With 1.6V on the input, resistor  $R_8$ , see Figure 3, is adjusted until 200 mV is across  $R_R$ . Figure 4 is the measured transfer function using a calibrated voltage source. The worst case deviation from a straight line was  $-8\text{ }\mu\text{A}$ , which is not observable on the graph in Figure 4.

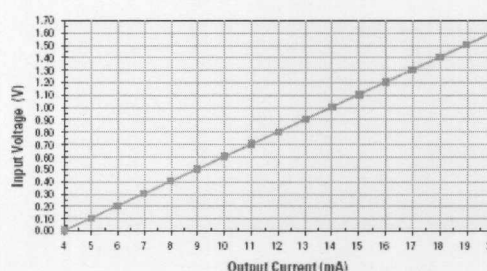


Figure 4. Output Current vs Input Voltage

In summary, by using a selection of components that function with very low supply voltages a current loop transmitter can be designed that operates with as little as 1.3V.

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